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Whenever an imaging spectrometer is employed, pixel-to-pixel variations and changes in sensitivity, gain, or noise can distort a recorded image. As a result, some form of normalization is required if faithful images are to be recorded. Although a number of alternative approaches have been explored for such normalization, the method described in this paper is novel in its effectiveness and simplicity. In this approach, a chemiluminescente substance is introduced into a flat sample cell whose dimensions are large enough to ensure uniform coverage of the photodector array of interest. Because the chemiluminescence solution is homogeneous, it can be used to uniformly irradiate the imaging detector; recording of the resulting image then indicates any variations that exist across the detecotr face. In turn, the array of data so produced serves nicely as a normalization vehicle for later images to be taken.

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CORRECTION OF GAIN AND OPTICAL THROUGHPUT VARIATIONS IN A TWO-DIMENSIONAL IMAGING SPECTROMETER

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Index Headings: Instrumentation, Array Detectors, Imaging Spectrometers, Normalization

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INTRODUCTION

Imaging spectrometry is a field which has demonstrated remarkable growth in recent years. The driving force behind the interest in this field is the additional information made available when both spatially and spectrally resolved signals are collected simultaneously. In the past, these data have typically been collected sequentially (point by point) or by means of photographic detection. However, several imaging spectrometers have recently been described which permit collection of spatially-resolved, wavelength-specific images with multi-dimensional detector arrays (e.g., vidicon tubes, photodiode arrays, charge-transfer detectors, etc.).[1,2] These spectrometers allow an image to be acquired much more rapidly than was previously possible, and therefore enable new experiments which previously were difficult or impossible to perform. Unfortunately, these spectrometers also suffer from their own unique set of problems, including variations in the optical throughput of the spectrometer as a function of spatial position in the image plane (e.g., vignetting), and differences in pixel sensitivity on the detector array. In the most extreme case, these problems can overwhelm the signal and cause them to be unusable.

Fortunately, many of the problems with imaging spectrometers are simple to overcome. If an object with constant radiance is viewed with an imaging spectrometer, simple normalization schemes can be used to correct for signal distortion.[3,4] The primary difficulty with this correction method is in generating a source which is uniformly radiant over the entire area being imaged. When the field of view is small, this problem is relatively simple to overcome. However, as the area to be imaged increases, generating this "flat field" becomes a formidable task.

Two methods have traditionally been used for generating an image plane of uniform radiance; backlighting a diffusion screen and image scrambling with an integrating sphere. The diffusion-screen method, while relatively inexpensive, suffers from the problem that uneven illumination of the screen can occur if the screen and illumination source are not positioned with care. In contrast, integrating spheres are relatively simple to set up and operate, but their expense can discourage their use.

An alternative approach to generating a uniformly illuminated field is to produce a uniformly emitting surface. In the work described here, this latter method is implemented by placing a homogeneous solution of a chemiluminescent compound in a transparent cell of uniform thickness. The dimensions of the cell and the homogeneity of the solution are easily controlled so constant emission over each unit of surface area is assured. Furthermore, this concept is easily scaled to whatever size is convenient. As will be demonstrated, construction of the equipment needed to make the measurements can be simple and easily within the budget of most laboratories. What follows is a brief description of our initial attempt to employ this novel method to normalize an imaging spectrometer.

EXPERIMENTAL

The monochromatic imaging spectrometer used in this study has been described previously.[1] Briefly, light from the source is collimated with a plano-convex lens (f.l.=35 cm) and then fed into a

Czerny-Turner monochromator (Model EU-700, Heath Inc.). The monochromator isolates a particular wavelength (spectral bandpass of 4 nm) and passes collimated psuedo-monochromatic radiation through the exit slit. A second lens (f.l.=15 cm), placed just beyond the exit slit, forms the monochromatic image of the source on the face of a charge-coupled device (CCD) camera (Thomson CFS TH7882CDA CCD with UV response coating, Model CC200 camera controller, CH220 liquid cooled camera head, LC200 liquid-circulation unit, CE200 camera electronics unit with a 50 kHz 14-bit A/D convertor, RS170 video option, Photometrics Ltd.). The detector array was maintained at -50 C to minimize dark current. Additionally, a dark frame was collected and subtracted from each data image to help minimize the differences in dark signal for different integration times. Finally, the image frame from the camera controller was transferred to a IBM AT compatible computer (386 Tower, Northgate Inc.) for data processing and display.

The cell used to contain the chemiluminescent compound was constructed from two 3-inch diameter glass windows. A Viton O-ring was sandwiched between the glass plates to provide a space for the chemiluminescent material. Clamps at four positions on the perimeter of the cell insured that the chemiluminescent solution did not leak from the cell. Once the cell was assembled, the chemiluminescent material was injected via a syringe into the space between the two glass plates. The syringe needle was left imbedded in the O-ring to permit the small quantity of gas produced by the chemical reaction to escape.

RESULTS AND DISCUSSION

The choice of the chemiluminescent compound to be used in the normalization procedure is critical for simple normalization of the spectrometer. Initial investigations employed luminol as the chemiluminescent substance. Luminol was reacted with an alkaline solution of hydrogen peroxide and potassium ferricyanide to produce a chemiluminescent solution. Unfortunately, the reaction was nearly complete several seconds after initiation, rendering the mixture of limited practical utility. Increasing solvent viscosity to slow the reaction kinetics provided only marginally better reaction times. Thus, luminol was determined to be unacceptable for the proposed application.

A more satisfactory group of chemiluminescent compounds are the reagents inside chemiluminescent Safety Lights which are commonly available from a hardware or camping-supply outlet. Figure 1 shows the emission spectrum for one example of this type of product (Cyalume® 12-hour Green Safety-Light, American Cyanamid). Each light stick contained approximately 9 mL of a proprietary fluid which the manufacturer claims will radiate for 8 to 12 hours. Analysis of the decay of chemiluminescence reveals that two species are emitting. Both species exhibit first-order luminescence decay kinetics with half-lives of 1.28 and 33.51 minutes and emission spectral maxima at 509 and 515 nm respectively. Other chemiluminescent solutions are available from the same manufacturer with emission maxima in the blue, yellow-green and red portions of the spectrum.

To confirm that the chemiluminescent cell radiance is uniform, a cell was prepared and imaged point by point into a small monochromator. The PMT anode current was monitored as a function of viewing position in the cell. Forty-seven separate measurements were collected in the central region of the cell (2.5 cm. x 3.7 cm.). The relative standard deviation of these measurements was 1.7%. Most of this variation in radiance was attributed to a gradual change in thickness of the cell from one side to the other. In turn, this change in thickness was most likely caused by either a change in the thickness of the cell O-ring, or a gradient in the compression of the O-ring. This variation was determined to be acceptable for our applications, but could be reduced with a redesigned sample cell.

If a uniformly illuminated field is imaged with the spectrometer described here, the image will be nonuniform because of spatially dependent disparities in optical throughput, pixel-to-pixel variations in sensitivity of the CCD chip, and differences in the offset signal from individual detector-array pixels. The highly linear response of the CCD permits correction of this image distortion with a simple linear-regression algorithm.

A correction (normalization) file which contains both gain and offset values for each pixel was generated by applying linear-regression analysis to four "flat-field" images collected with the instrument and which have different integration times. This procedure could have also been implemented by using neutral-density filters at the entrance of the imaging spectrometer to simulate different image intensities. These files were then applied to the raw data file (an image from a cell which was rotated 180^{0} from the position where the regression images were collected) to help correct for instrument-induced distortions of the data. Correction of the newly acquired data is accomplished by first subtracting the offset value (regression y-intercept value) from the raw data array, then dividing each data point in this new array by its sensitivity (slope).

Figure 2a shows the unnormalized (raw) spatial image produced by the monochromatic imaging spectrometer of the cell containing the chemiluminescent fluid. Clearly, there are spatially dependent differences in the efficiency with which radiation is detected. As expected, transmission of light is most efficient in the center of the image and gradually decreases towards the edge of the image frame. Overall, the relative standard deviation of this surface is 10.9%.

Figure 2b shows the data obtained when a uniformly illuminated object is monitored with the monochromatic imaging spectrometer and normalized using the procedure described above. Gross differences in intensity that are apparent near the edge of the field of view in Figure 2a are almost completely compensated in Fig. 2b. Small random fluctuations in the image surface are the result of statistical fluctuations in the raw data. Because this noise is random, the normalization procedure will not correct for its effects. Furthermore, the degradation of the signal-to-noise ratio near the edge of the array cannot be corrected. The relative standard deviation of this surface is 2.47%, a significant improvement over the uncorrected image. Furthermore, the image distortions which remain uncorrected could be further reduced with appropriate digital-filtering techniques [5].

CONCLUSIONS

There are three important points which are evident in the work described here. First, spatially dependent differences in optical throughput are observed with the type of imaging spectrometer instrument described here. Unless these variations are corrected, quantitative interpretation of the resulting images is difficult. Secondly, for this instrument, simple linear regression techniques can be used to normalize the spectrometer images. Finally, the method described here for generating an evenly illuminated field is both simple and inexpensive. Its primary disadvantage is the relatively limited spectral range which can be covered with available chemiluminescent materials. However, for many applications, this limited spectral coverage is not a significant shortcoming; in such applications this method is effective for detector array and imaging-spectrometer normalization.

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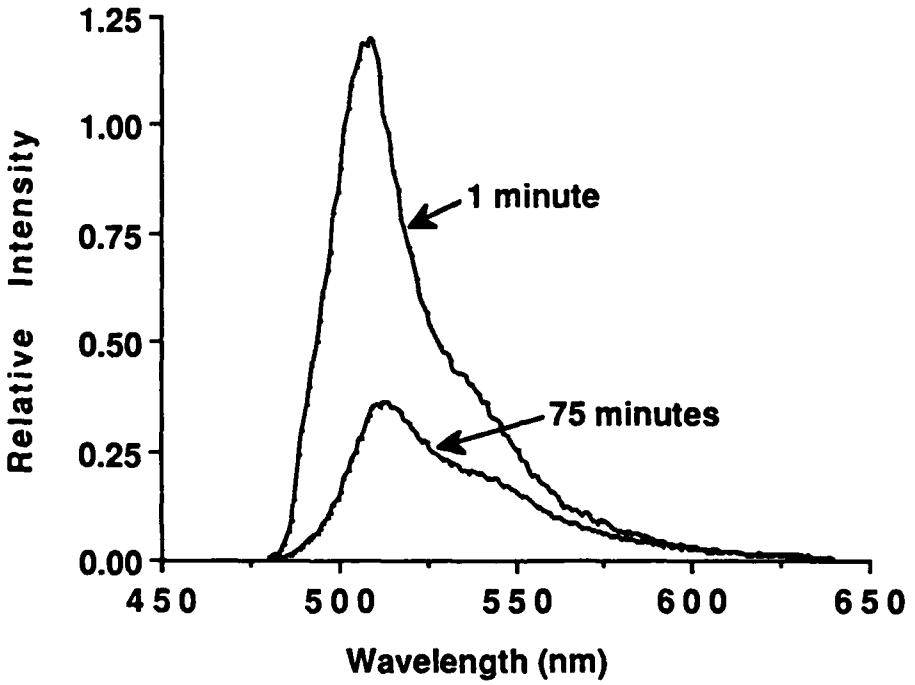
FIGURE CAPTIONS

Figure 1. Emission spectra for Cyalum® Green Safety-Light 1 and 75 minutes after the reaction is initiated.

Figure 2. Spatially resolved image of a sample cell used to generate normalization data files, (a) Raw data from imaging spectrometer, (b) Data from Fig. 2a which have been normalized.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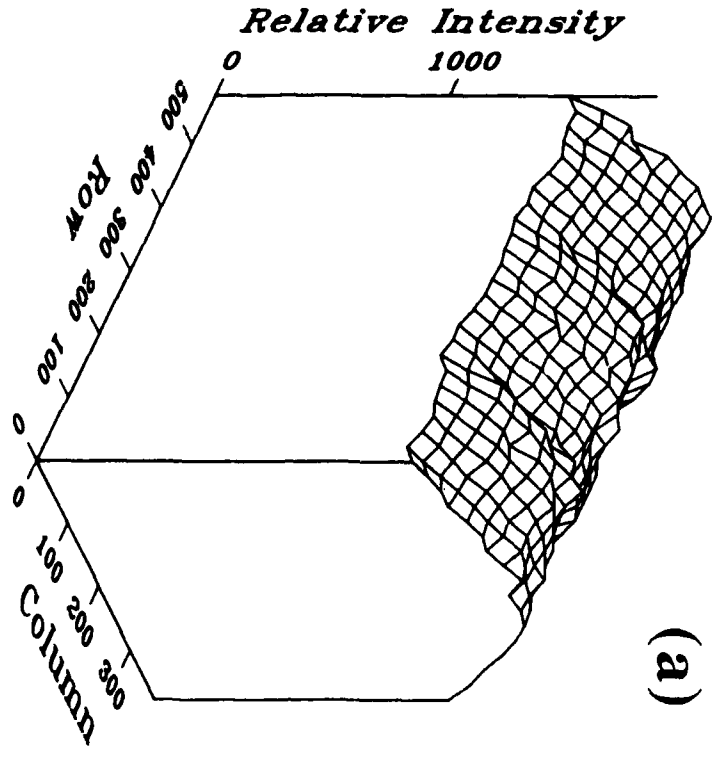
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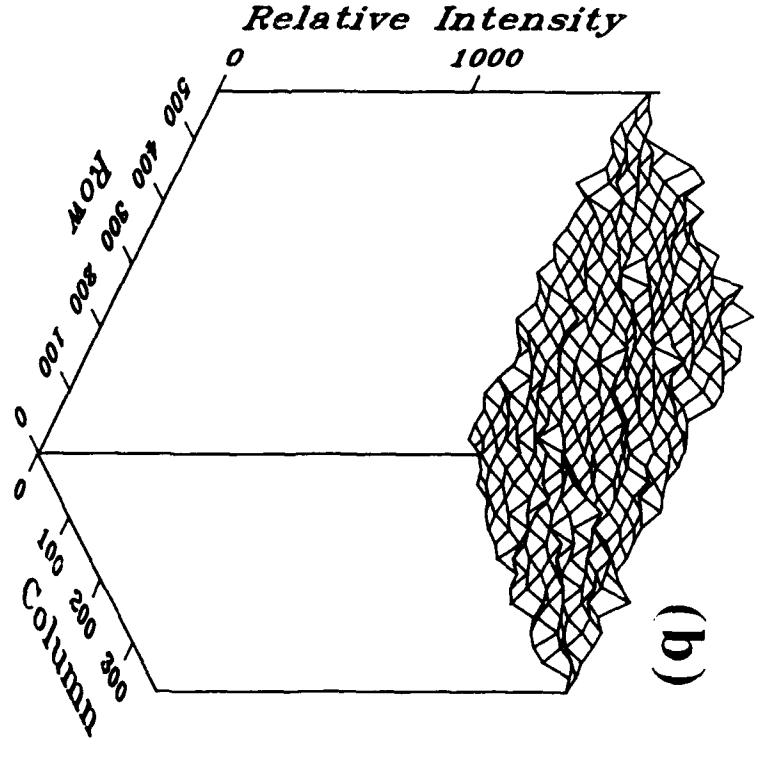
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